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Why timing matters in a coastal sea: Trends, variability and tipping points in the Strait of Georgia, Canada

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A B S T R A C T

In this paper we review available time series for the Strait of Georgia to identify trends and variability in physical and biogeochemical properties. Change is partly imported from the open ocean and partly results from processes operating at the local scale. The largest component of variation occurs at the seasonal scale, although the timing in annual cycles differs among properties. A second important component of variability is associated with cycles at the decadal (PDO) or sub-decadal scales (ENSO). Long-term trends are superimposed on the variability.

Seawater in the Strait has been warming at >1 °C/century, as has the freshwater entering from the Fraser River. The number of days when Fraser River temperature exceeds the 18 °C threshold for salmon migration has increased over the last 50 years. In the Strait itself, the temperature increases are of the same magnitude in deep water as at the surface, but are probably more significant in the deeper water because of the narrow seasonal range of temperature at depth. The change in annual freshwater discharge from the Fraser River over the period of record is much smaller than the interannual variability, but there has been a notable change in timing, with more of the discharge occurring in spring and less in summer. This, together with warming, may be producing an earlier spring bloom and an altered coupling between phytoplankton and zooplankton. Sea-level rise is occurring within the Strait at rates similar to other locations, but the presence of the large Fraser River delta, undergoing industrial and municipal development, makes this region especially sensitive to sea-level rise and to increased storm activity.

Variability in bottom water properties is predominantly forced from outside the basin, depending especially on the timing of coastal upwelling, which delivers water containing high nutrients and low dissolved O_2 and pH. As in the global ocean, pH in the Strait is likely declining, but records remain too short to produce a confident assessment.

The timing of geochemical cycles in the Strait of Georgia is delicately poised, with, for example, deep-water oxygen reaching a hypoxic tolerance threshold in the spring, just before deep-water renewal replenishes the oxygen from outside. However, long-term trends in oxygen, temperature and timing of biological activity may lead to the crossing of crucial biological tipping points within this century. Timing is particularly important for monitoring. Relatively long records for basic water properties like temperature and salinity are accompanied by much shorter records for biogeochemical properties like dissolved O_2, pH, nutrients and vertical flux, making it difficult to assemble a clear picture of the sorts of changes that may be occurring in the latter. A confident assessment of the ecological resilience of the Strait of Georgia will require longer time series of biological and geochemical properties that are collected with consideration for the strong seasonal variability.

1. Introduction

The marine environment varies on time scales of hours to millennia. The longer time scales of variability, which are predominantly the focus of climate-change studies, tend to be driven by regional or global climatic oscillations variously assigned to processes like El Niño Southern Oscillation events (ENSO: ~one year), the Pacific Decadal Oscillation (20–30 years) or ice age cycles (100,000 years) (e.g., see Ruddiman, 2000). During the past 200 years human activities have introduced an unprecedented kind of global forcing (Steffen et al., 2011): a rapid, persistent loading of the atmosphere with greenhouse gases (GHG), which changes the global temperature balance (IPCC, 2007) and acidifies the oceans with carbonic acid (Orr et al., 2005). The most optimistic projections based on recent generations of biogeochemical climate models suggest that, at least, these global changes will persist over several hundreds of years (IPCC, 2007). Human activities over short-term, seasonal,

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multi-annual and multi-decadal time scales have also altered global ocean systems in other ways, including selective harvesting from food webs (Pauly et al., 2001), permitting the migration of invasive species accidentally or deliberately (Occhipinti-Ambrogi, 2007), changing the hydrology of almost every large river (Dynesius and Nilsson, 1994), adding large quantities of macro-nutrients to coastal seas (e.g., phosphorus and fixed nitrogen Rockström et al., 2009), and releasing toxic substances like Hg, PCBs, DDT, pharmaceuticals and artificial radionuclides. Our efforts to determine what effect these sorts of human activities are having on marine systems must take into consideration natural variability occurring at various time scales, because variability can both cloud our ability to assign cause and combine with human forcing to exacerbate effects.

Coastal waters are especially variable given their intermediate position between land and the open ocean. They are affected by freshwater inflow and human activities such as urbanisation, marine traffic and disposal of wastes, as well as by global changes in the larger ocean (Hare and Mantua, 2000; Overland et al., 2006). In mid-latitude coastal oceans seasonal variability is driven by winds, freshwater runoff and solar radiation, which affect deep-water renewal, water exchange, air–sea gas exchange, mixing and estuarine circulation. Together these processes provide the setting for primary production, the basis of the food web. How the coastal ocean receives or responds to these various types of forcing depends to a large extent on local characteristics, including bathymetry, water residence time and depth of free exchange with the outer coast.

The variability observed for any seawater property, therefore, depends on the scale of the observations, and our ability to discuss temporal variability in ocean properties at any given scale depends on having at hand data sets of appropriate length- and time-resolution. For most geochemical properties in coastal waters this presents an enormous challenge at time scales longer than a decade or shorter than a season because we do not have time series of sufficient resolution or length.

The Strait of Georgia (SofG), a semi-enclosed coastal sea between Vancouver Island and the west coast of Canada (Fig. 1), provides a natural laboratory in which to study variability over a wide range of time-scales. The objective of this paper is to review the trends and variability in physical and biogeochemical properties of the SofG over days to decades. We consider variability in the SofG in the context of large-scale processes known to affect the northeastern Pacific Ocean (e.g., El Nino Southern Oscillation (ENSO)), and local processes operating within the Strait of (e.g., Fraser River inflow). We identify the dominant time-scale of variability and show how long-term trends interact with variability to affect geochemical cycles and tipping points in the Strait of Georgia.

2. Regional setting

The physical circulation of the Strait of Georgia has been studied extensively over the past several decades (e.g., Amos et al., in press; LeBlond et al., 1991; Masson, 2002, 2006; Masson and Cummins, 2004, 2007; Pawlowicz et al., 2007; Thomson, 1981, 1994; Waldichuk, 1957). Briefly, freshwater inflow, mainly from the Fraser River, drives an estuarine circulation, with inflow at depth primarily through Juan de Fuca Strait (Fig. 1). In Haro Strait the inflowing water is mixed

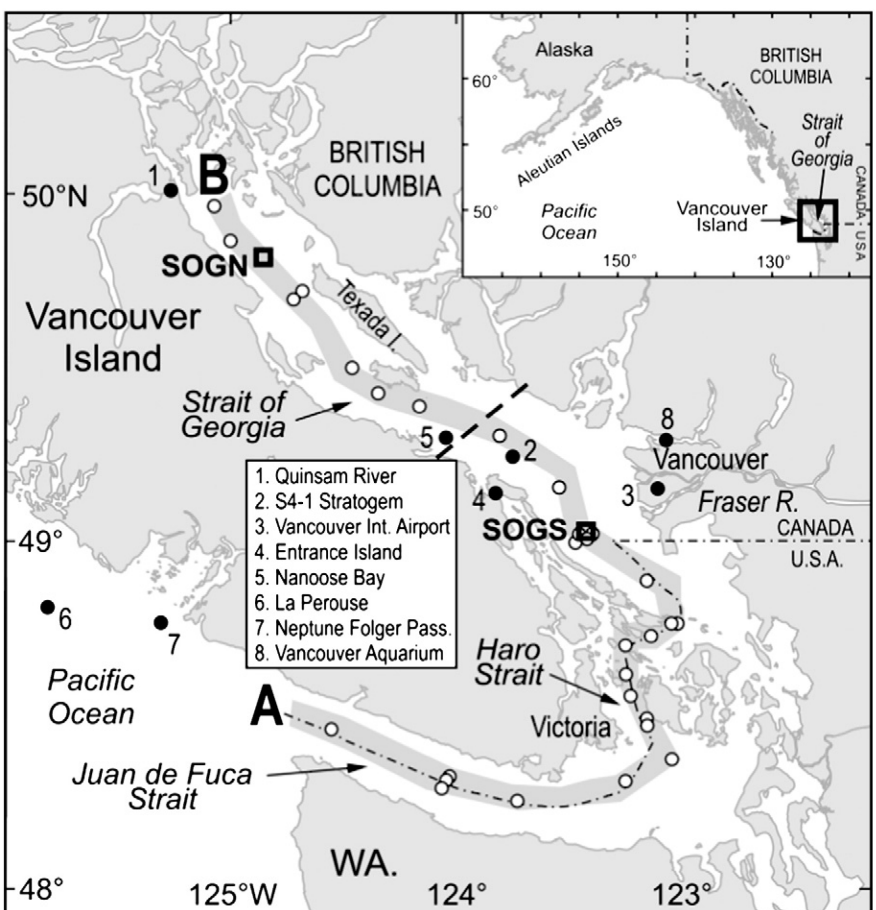

Fig. 1. The Strait of Georgia showing the geographic features and locations discussed in the text. The open circles denote a time-series section maintained for Strait of Georgia water properties (e.g., see Masson, 2006). SOGN and SOGS show the location of two time-series moorings with instruments monitoring dissolved oxygen, particle flux and other parameters.

vigorously by tidal currents before entering the SofG. In late spring and late summer, deep water renewal events replace both the bottom and intermediate water of the Strait. Circulation is modulated by winds, variations in river discharge and the spring–neap tidal cycle.

Over the last two decades, biological (e.g. Allen and Wolfe, 2013; Mackas and Harrison, 1997; Mackas et al., 2013; Yin et al., 1997), and geochemical studies (e.g., Allen and Wolfe, 2013; Johannessen and Macdonald, 2009; Marliave et al., 2011; Pawlowicz et al., 2007) have broadened the understanding of this coastal sea, and now provide the basis to project temporal change in biogeochemical cycles. Numerical models (Foreman et al., 2011; Jakob et al., 2003; Li et al., 1999; Merryfield et al., 2009; Morrison et al., 2002, 2012) have projected what some of these changes might imply for the future of the Strait.

Early studies established the idea of a regional difference between the north and the south components of the SofG based on the more immediate connection with the Pacific Ocean at the southern end (Godin et al., 1981; Thomson, 1981, 1994; Waldichuk, 1957). More recent studies have shown that this zonal spatial variability is also a product of Fraser River inflow, which dominates the southern region (Johannessen et al., in press; Sutton et al., 2013). However, few studies have investigated the northern SofG.

3. Variability versus trends

Distinguishing between variability and trends depends on the choice of time frame. Variability usually refers to short-term variation about a mean, whereas a trend is considered to be a positive or negative drift in the mean over the time period in question. There are many well-known problems in assigning trends to time-series data, including the choice of start and stop times over which a trend is determined. A trend found in a ten-year time series might be viewed as low-frequency variation at the century scale, and so on, as the record becomes longer. Given the relatively short duration of time series for most of the properties in SofG waters, trends can be assigned only with a great deal of caution. Here we will use the term trend only to refer to multi-decadal time scales or to situations where we have reason to believe that something outside of historical norms is occurring (e.g., increasing seawater temperature and declining pH).

4. Variability and trends in external forcings: fresh water, winds and sea-level rise

Fresh water and winds provide dominant, climatically-sensitive controls on the variability of water properties and sea level in the Strait of Georgia (SofG). Inflow from the Fraser River and many smaller rivers, together with net precipitation, provides stratification and salt water dilution and forces estuarine circulation. Winds force circulation, produce mixing and drive upwelling along the outer coast, the region that supplies the SofG with its salt water (e.g., see Thomson, 1981). Rivers also provide a seasonally-modulated supply of nutrients, organic carbon, particulate matter and other components of direct importance to the Strait's biogeochemical cycles.

Two other system variables, tides and solar radiation, also provide much of the variability. These two forms of forcing derive from predictable, relatively consistent planetary cycles. However, the effects of tides and solar radiation on coastal waters are subject to added variability deriving from climate factors. In the case of tides, storm surge and relative sea-level rise come into play, while solar radiation incident on the ocean surface may be modulated by fog and cloud cover and, within the water, by transmissivity.

4.1. Freshwater temperature, discharge and precipitation

Fraser River temperature (1941–2006) and stream flow (1912–present) provide reliable and consistent records from which to evaluate trends and variability (Foreman et al., 2001; Morrison et al., 2002; Patterson et al., 2007). Between 1953 and 2006 summer (June–August) temperature in the Fraser River increased at a rate equivalent to 3.3 ± 1.7 °C per century (dashed line on Fig. 2a), although the increase might also be described as a step change in about 1986 (Foreman et al., 2001; Morrison et al., 2002). The total annual flow shows no statistically significant secular trend (1.6 ± 8 km^3 per century ($p = 0.7$)) over this same period (Fig. 2b).

The rise in daily summer river water temperature is particularly noteworthy, as it has led to an increase in the number of days during each summer when the temperature exceeds 18 °C (Fig. 3a), a threshold that may limit or prevent salmon migration (Martins et al., 2010; Rand et al., 2006).

The Fraser River hydrograph has become flatter (Fig. 3b), indicating a shift from predominantly snow-fed (spring/summer freshet) toward predominantly rain-fed runoff (multiple autumn and winter peaks). The difference between the earliest decade of record and the latest (2001–2011 minus 1912–1921 average daily flows) (Fig. 3c) indicates that, overall, the total flow was ~14% lower in the more recent decade. The major change has been a considerable decline in flow between mid-June and early September accompanied by smaller, variable increases in flow throughout the rest of the year and especially in April–May. This shift can also be recognized by the observation that one-third and one-half of the annual cumulative flows are now reached earlier by 11 and 9 days per century, respectively (1912–1995 observations) (Foreman et al., 2001). Simulations suggest that if these trends continue, by the end of the 21st Century the Fraser River discharge will be dominated by rainfall (Morrison et al., 2002).

The total annual precipitation in southern British Columbia increased by 9% (coastal area) and 14% (BC interior) over the 20th Century (Mekis and Hogg, 1999, Table 3 ($p < 0.05$)), with most of the increase occurring over 1920–1970 (Jakob et al., 2003). In addition there has been a significant increase in the frequency of short-duration (<5 min) rainfall since the 1990s compared to the pre-1977 period (Jakob et al., 2003). Fig. 4 shows the minimum number of days required in any given year to accumulate half the annual rainfall. In this calculation, a year of consistent rainfall, where every day was the same, would accumulate half of the rainfall in 183 days, while a year with many heavy rainstorms would require fewer days. The main trend seems to be an increase in the interannual variability of rainfall intensity. Whereas the offset between the means calculated for the intervals 1938–1977 and 1978–2010 is not statistically significant ($p = 0.052$), the variances in these two intervals are (Bartlett's test, $p < 0.025$). For example, in 1981 it required 35 days to accumulate half the rain, but in 2003 only 19 days. These observations do not show an intensifying global hydrological cycle (e.g., Huntington, 2006) manifested as higher total precipitation, but there does recently appear to be a more sporadic occurrence of high-precipitation events (cf. Min et al., 2011).

At the decadal scale, snowpack, river discharge, river temperature and precipitation are affected by the Pacific Decadal Oscillation (PDO) (e.g., Fleming and Quilty, 2006; Fleming and Whitfield, 2010; Foreman et al., 2001; Jakob et al., 2003; Morrison et al., 2002; Thorne and Woo, 2011; Whitfield et al., 2010). Specifically, warm winter air temperatures and anomalously low precipitation during positive PDO years lead to reduced snowpack in Washington State and British Columbia (Cayan, 1996; Mantua et al., 1997). In principle, this should lead to reduced spring runoff for snow-dominated rivers like the Fraser, but the complexity of the various processes contributing to stream flow presently precludes prediction (Dery et al., 2012). Recent studies (Fleming and Whitfield, 2010; Fleming et al., 2007; Whitfield et al., 2010) assessing the effect of the PDO on temperature, precipitation, spring snowpack, and streamflow throughout British Columbia found significant warming in early months of the year at Victoria during the positive PDO phase, and a significant increase in precipitation in early fall and late winter (Fig. 5a). Snowpack volume estimates at Mission Creek in the Fraser River valley suggest that, during the positive PDO phase, the snowpack melts over a shorter period and contributes a smaller volume of water

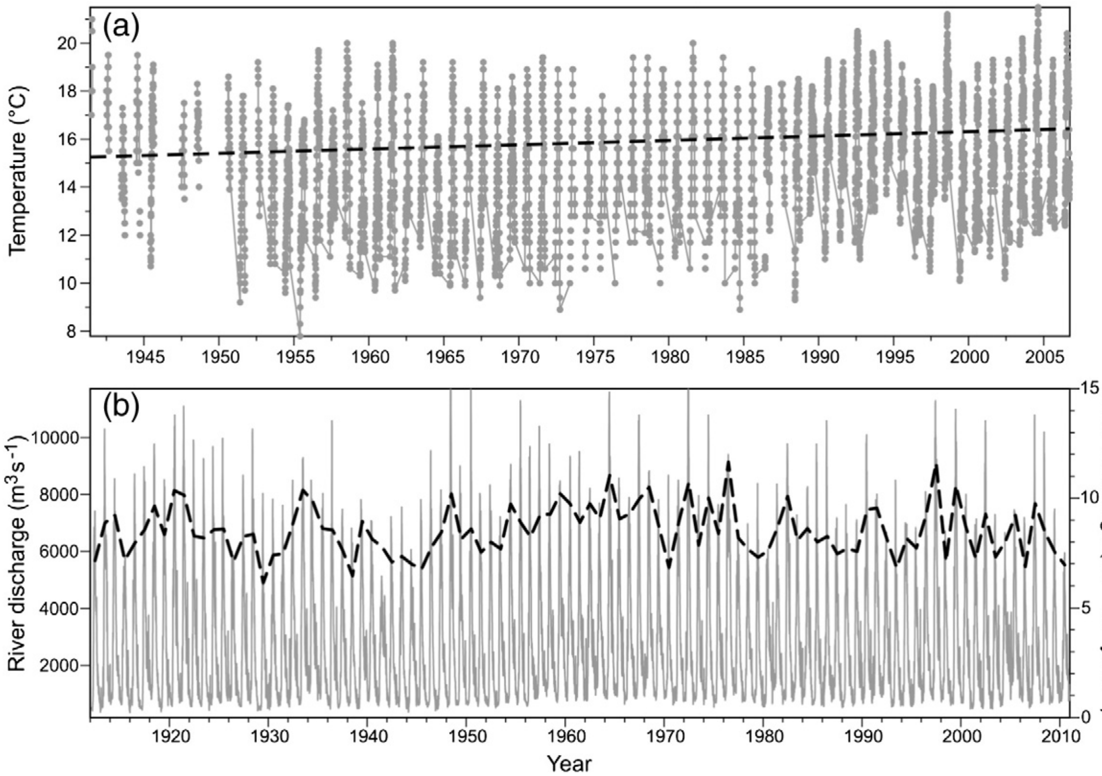

Fig. 2. Fraser River records of a) temperature and b) stream flow. The dashed line in panel a shows a significant long-term trend in warming (3.3 ± 1.7 °C per century (95% CI)) for the summer data (June–August), although the increase could also be described as a step change in about 1986. The dashed line in the panel b shows mean annual flow, which exhibits no significant trend over the period of record (1.6 ± 8 km^3 per century ($p = 0.7$)).

(Whitfield et al., 2010), leading to lower peak freshet during the warm PDO phase (Fleming et al., 2007).

At the annual scale, the El Niño Southern Oscillation (ENSO) contributes to interannual variation in precipitation. During the El Niño phase, winter and spring precipitations decrease (Fig. 5b, Victoria precipitation). At these times dry conditions generally prevail in Southern BC, and the Fraser River discharge is low (Dery et al., 2012; Whitfield et al., 2010).

The source of moisture contributing to precipitation in the Fraser Basin appears to vary among years based on a 6-year record of $\delta^{18}O$ composition of the Fraser River water at Hope (Fig. 6) (Macdonald et al., 2009). In 1995 the $\delta^{18}O$ was anomalously high, which likely indicates a more direct, southerly source of moisture, possibly related to storm tracks (e.g., Tremoy et al., 2012). A change in the source of the water implies that other airborne properties, like semi-volatile or particulate contaminants, would likewise be subject to change (Noel et al., 2009; Wilkening et al., 2000), although no data have been collected to confirm this.

Freshwater inflow from the Fraser and other rivers provides a major component of forcing in the SofG. The data presented in Figs. 2b and 5a, b show that the largest component of variability in freshwater inflow and precipitation is seasonal, far exceeding the longer-term variability (Table 1). Comparison of the seasonal climatology of the Fraser River (Fig. 3b), presently dominated by snowmelt, and the Quinsam River (Fig. 7a), which represents small, precipitation-dominated rivers, shows that the latter also has strong seasonality, but this is dominated by episodic rainfall between October and April, rather than by a strong spring freshet. Total annual flow of the Quinsam (Fig. 7a) shows no significant trend (regression slope $= -0.01 \pm 0.03$ m^3 s^{-1} yr^{-1} ($p = 0.46$)) or evidence of decadal-scale cycles over the interval of measurement (1957–2010). The timing of the discharge might have changed during those 50 years, but, if so, the change is not so dramatic as for the Fraser River (Fig. 7b,c).

4.2. Winds

Wind patterns on the outer coast of BC determine upwelling and downwelling, which set the stage for water properties in the SofG. Downwelling occurs mainly in winter, when the Aleutian Low intensifies near BC coastal waters, while the summer upwelling occurs under the intensification of the Pacific High. Long-term observations of coastal winds suggest the persistence of more intense summer upwelling since the late 1990s (see Hourston and Thomson p27 in Irvine and Crawford, 2012). Since 1959 the strength of upwelling has increased by 20 ± 1.7 m^3 s^{-1} per 100 m of coastline (95% CI), and downwelling has increased by 28 ± 2.2 m^3 s^{-1} per 100 m of coastline due to a general increase in alongshore wind stress (Foreman et al., 2011, Fig. 8a). Merryfield et al. (2009) predict a further 5–10% increase in upwelling by 2100. The timing of upwelling has also changed. The onset of upwelling has become later and the upwelling season shorter over the last 40 years, at a rate of 0.88 days/year (Foreman et al., 2011, Fig. 8b). The upwelling season is several weeks shorter now than it was in the 1960s. The daily upwelling climatology (Fig. 8b inset), however, shows that upwelling and downwelling exhibit strong short-term variability.

The timing of upwelling and downwelling is important because it results in variability in the chemistry and density of the water entering along the bottom of the Strait of Juan de Fuca and replacing SofG basin-water through Haro Strait. A time series of dissolved O_2 concentration at 100 m depth in Folger Passage near the entrance to Juan de Fuca Strait (Fig. 9) illustrates the effect of upwelling. A change in the timing of the onset of upwelling in spring has the greatest potential to

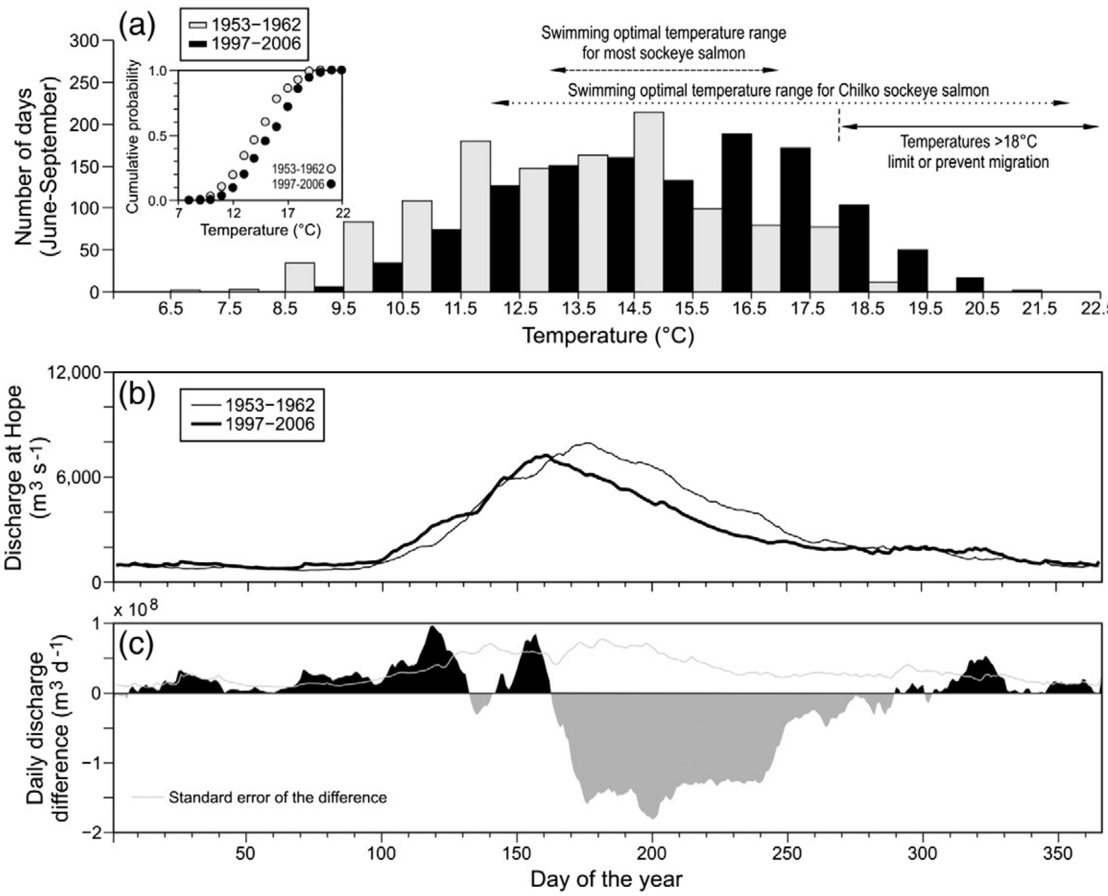

Fig. 3. Trends in the Fraser River. Panel a) shows a comparison between 1953–1962 and 1997–2006 of the distributions of summer temperatures (June–September) as the number of days observed partitioned into 1 °C intervals. The frequency distribution (inset panel) shows that higher temperatures have been observed in the later period (Kolmogorov–Smirnov non-parametric test ($p > 0.001$). Panel b) shows the mean hydrograph (volume discharge, $m^3\ s^{-1}$) for 1912–1921 and 2001–2010; and Panel c) the difference between the two hydrographs (latest minus earliest, $m^3\ d^{-1}$). The standard error (SE) for the difference is also plotted as a dotted line.

alter properties resupplying SofG basin water based on the gradients in dissolved O_2 at that time. Given the regeneration cycle in the ocean, we expect similar effects for nutrients and other bioactive components (e.g., Cd, Zn).

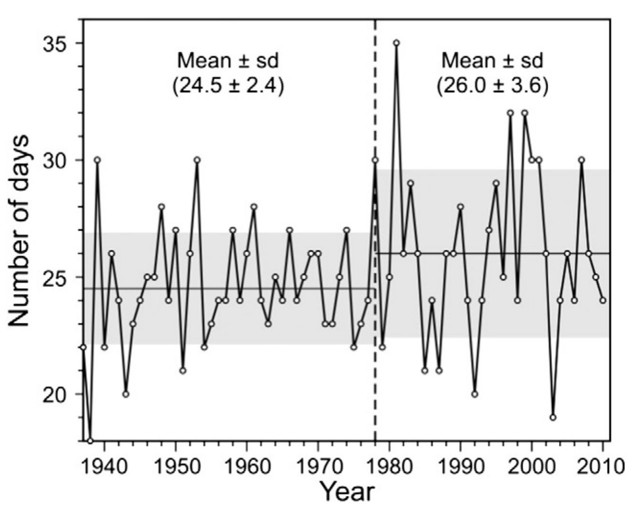

Fig. 4. The minimum number of days required in any given year to accumulate half of the annual cumulative rainfall (based on the Vancouver International Airport record from 1938 to 2010). The means for the intervals 1938–1977 (24.5) and 1978–2010 (26.0) are not statistically different (t-test $p = 0.052$). The standard deviations (shaded areas) are greater during the later interval ($p < 0.025$; Bartlett's test).

4.3. Sea level

The global estimated sea-level rise (SLR) due to thermal expansion and freshwater input is likely to be 0.4–1.0 m or more by the end of the century (Hansen et al., 2007; Solomon et al., 2009). The SofG will be subject to this general rise, modified locally by isostatic rebound (or depression) of land (see for example, Gehrels et al., 2011; Syvitski and Kettner, 2011). SLR also responds locally to the density of the water (less dense water associated with seasonal run-off, for example, might impart a SLR of ~≤10 cm) and to atmospheric pressure (~± 35 cm). It is not clear how these various effects will manifest themselves in the SofG, but salinity variations are likely to be a leading factor (e.g., Cummins and Masson, 2011; Thomson et al., 2008). An analysis of the record of wind and sea level collected by buoys deployed along the Pacific coast of North America between 1981 and 2003 together with ocean hindcasts of conditions during the early 20th century suggests a regional acceleration of SLR along the Pacific Coast concomitant to a new wind regime shift associated with the PDO (Bromirski et al., 2005).

The local net effect of these various processes, measured at Victoria Harbour, BC, has been an increase of the relative sea level by ~6 cm per century (Thomson et al., 2008). Projections suggest that sea level will increase by a further 50 cm by the end of the century (Fig. 10) (Thomson et al., 2008), although an increase of over 100 cm is deemed possible (Hansen, 2005). Storm surges have the potential to add as much as 1.8 m episodically, based on historical records, and are predicted to occur more frequently in the future (e.g.,. Bromirski et al., 2005; Changnon, 2007).

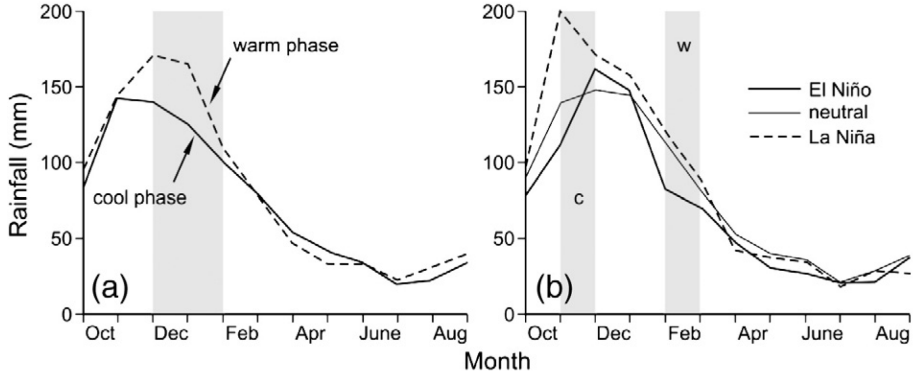

Fig. 5. A comparison of rainfall at Victoria showing a) the effect of PDO warm (dotted line) and cool (solid line) phases and b) the effect of ENSO phases (after Fleming et al., 2007). Months with averages showing significant differences ($p < 0.05$) are shaded; in Panel b), the c denotes a difference between La Niña and the neutral state, and w denotes a difference between El Niño and the neutral state.

The coast of BC has been subject to sea level change over the past 10,000 years due partly to wastage of large continental glaciers contributing ~125 m of water to the global ocean (e.g., Fairbanks, 1989) and partly to local effects such as isostatic rebound and delta sediment compaction. It is estimated by Clague et al. (1982) that relative sea level for the Fraser Lowland has increased by 12 m or more over the past ~8000 years. Sensitivity of shore zones to SLR varies around the SofG depending on coastal soil/rock composition and vertical gradient of the backshore. The Fraser delta is especially sensitive to SLR due to the low gradient of the land, and to a substrate dominated by mud (Shaw et al., 1998).

Global sea-level rise is a relentless trend leading to increased coastal erosion, potentially releasing a number of substances (e.g., organic carbon, nutrients and contaminants) into the coastal zone, and altering nearshore bathymetry with effects on neritic plants and animals. Large accretionary deltas are likely to be among the most sensitive locations to SLR, especially where they have been developed by human activities (Little, 2013). How relative SLR will affect the Strait, therefore, will very much depend on human response in the coming decades (Johannessen and Macdonald, 2009); will we construct ramparts against the ocean to protect developed areas, or will we withdraw as the ocean encroaches?

5. Variability and trends in water properties of the Strait of Georgia

5.1. Temperature

Temperature provides the longest time series from which to evaluate variability in surface water (Fig. 11a) and deep water (Fig. 11b) of the SofG. Temperature has been recorded in a variety of ways but with sufficient consistency among methods to develop an empirical image of change throughout the water column in the SofG (Masson and Cummins, 2007) and for surface water near BC lighthouses (Amos et al., in press). Lighthouse records of SST were initiated before 1940, but vertical profiles of the water-column began later, in 1950, with regular and consistent profiles collected at the Navy station in Nanoose Bay since 1970. Despite their high quality, however, these records are not yet long enough to evaluate trends and/or cycles over more than a few decades.

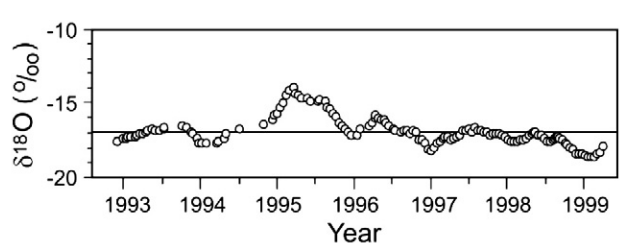

Fig. 6. A record of $\delta^{18}O$ for the Fraser River at Hope. Modified from Macdonald et al. (2009).

The SofG is warming at least as rapidly as the global ocean (see e.g., IPCC, 2007; Solomon et al., 2009). Projections based on current trends (Table 1) suggest that the mean water temperature could be 1.5–3 °C warmer by the end of the 21st century. In combination with an El Niño and a warm PDO phase, this could result in some years with average temperatures as much as 5 °C above the 20th Century climatology.

The climatology of the temperatures at the Nanoose Bay station (Fig. 12) reveals three major domains in the water column: 1) a surface layer (0–50 m) manifesting a large range in temperatures from < 7 °C in winter (Dec–Feb) to > 20 °C in summer (Jun–Sept) (Figs. 11a & 12); 2) a mid-depth layer (50–200 m, Masson, 2006; Masson and Cummins, 2007; Pawlowicz et al., 2007) where the temperature variation lags that of the surface by 2–3 months and shows a muted range of temperatures from < 8 °C in mid-April to ~10 °C in October–November; and 3) a deep layer (>200 m) manifesting temperatures of 8–10 °C, with a minimum in May–June, out of phase with that at mid-depth (Fig. 11b). Because the water column is strongly stratified by salinity, these temperatures do not force the circulation within the Strait in any significant way, but rather act as tracers of seasonal heating and properties of water entering from outside the SofG. The temperature variability in the surface water is dominated by seasonal solar irradiance together with the input of heat from the Fraser River in summer (Fig. 2a). In the mid-water column, temperature variation is due partly to vertical mixing and partly to water exchange via Haro Strait. Within the basin waters, temperatures are predominantly controlled by the signal brought in during bottom-water replacements, with cold water entering in May and warmer water in August.

An analysis of sea surface temperature (SST) in the SofG indicates an average increase since 1950 equivalent to 0.77 °C to 3.6 °C per century (developed from the data presented in Fig. 11a). Summer (June–August) trends over that time period have been 1.9 ± 0.2 °C/century at Entrance Island and 1.7 ± 0.2 °C/century for deep water at Nanoose Bay. Similar analysis yields winter (December–February) trends of 0.5 ± 0.1 °C/century (Entrance Island) and 1.5 ± 0.2 °C/century (Nanoose deep water). We note that a thorough analysis of all the lighthouse data collected in BC coastal waters (Amos et al., in press) found a mean increase in SST of 4.1 ± 0.6 °C/century for the SofG locations, which is near the top end of the range in rates determined from Fig. 11a. Likewise, the Nanoose Bay station data show a 3.3 ± 1.0 °C per century rate of increase in maximum seawater temperature at 4.5 m since 1970, and a 2.4 ± 1.0 °C per century rate of increase in deep-water maximum temperature (Fig. 11b; below 150 m, Nanoose Bay station) since 1970 (Masson and Cummins, 2007). The latter rate of increase considerably exceeds that observed for outer-coast deep water (about +1 ± 1 °C per century), or surface water collected at northern lighthouses (Amos et al., in press), because of the downward

Table 1
Variation in water properties associated with the Strait of Georgia according to time scales.

Property	Seasonal range	Interannual anomaly	Interdecadal variation	Multidecadal trend
Sea surface T	7–20 °C[a]	0.5–1 °C[b]	−0.4/+0.3 °C[c]	+(1.5–3.6) °C century^{-1}[d]
Mid-water T (50–200 m)	8–10 °C[a]	0.5–0.75 °C[b]	−0.4/+0.3 °C[c]	+2.4 °C century^{-1}[e]
Bottom T	8.5–9.5 °C[a]	0.5–0.75 °C[b]	−0.4/+0.3 °C[c]	+2.4 °C century^{-1}[e]
Sea surface S	15 or lower–27[a]	Small	Small	None[f]
Mid water S (50–200 m)	30–31 (Aug)[a]	Small	Small	Small
Bottom salinity	31 ± 0.2[a]	Small	Small	Small
Nutrients[g]				
Surface	N 0–30 µM			Small (+)
	P 0.5 or lower–2.5 µM			
	Si 10 or lower–60 µM			
300 m	N 15–40 µM			
	P 2–3 µM			
	Si 40–70 µM	?	?	Small (+)
Bottom	N 25–35 µM			
	P 2–3.5 µM			
	Si 50–70 µM	?	?	?
Dissolved O_2				
Surface	4–8+ mL L^{-1}[h]	Small	Small	T effect (−)
Bottom	2.5–4.5 mL L^{-1}(9)	?	?	−2.1 mL L^{-1}[i]
Sea level				
Tidal range	1.9–5 m[j]			
Storm surge	1.8 m[k]			
Sea level rise				+0.6 m century^{-1}[l]
Steric effect		~2×10^{-4} K^{-1}	~2×10^{-4} K^{-1}	
pH	7.1–8.2[m]	?	?	−0.75 century^{-1}[m]
Particle flux				
Fraser River				
Temperature	~0–22[n]	?	?	+1.8 °C century^{-1}[o]
Streamflow	1000–10,000 m^3 s^{-1}[o]	≤−1000 m^3 s^{-1} Freshet[p]	≤−1000 m^3 s^{-1} Freshet[q]	None

[a] BC Lighthouse data (Department of Fisheries & Oceans), Fig. 2 in Masson and Cummins (2007), STRATOGEM data.
[b] Fig. 4b in Masson and Cummins (2007).
[c] This paper(based on Mantua and Hare (2002)), Fig. 14.
[d] Lighthouse data, Masson and Cummins (2007) and Masson and Cummins (pers. comm.).
[e] Masson and Cummins (2007), 95% confidence interval of ±1 °C.
[f] Unshown sea surface salinity at Entrance Island, DFO data.
[g] This paper, Fig. 15a–c, STRATOGEM data.
[h] Surface O_2, STRATOGEM and DFO data, not shown.
[i] This paper, Fig. 17.
[j] Observed range of daily tides, Halverson and Pawlowicz (2008).
[k] Worst case scenario in BC coastal area, Danard et al. (2003).
[l] Victoria Harbour (Thomson et al., 2008).
[m] Vancouver Harbour time series by Vancouver Aquarium, Fig. 8 in Marliave et al (2011).
[n] Summer temperature, this paper Fig. 3a and Patterson et al. (2007).
[o] Foreman et al (2001), Morrison et al. (2002), this paper, Fig. 2a.
[p] El Nino phase, Fleming et al. (2007) Fig. 7, and Whitfield et al. (2010) Fig. 4.
[q] Fleming et al. (2007), Fig. 13 Fraser River.

mixing of warm surface water in the tidal passages or within the Strait (Masson and Cummins, 2007). The rate of increase of SofG deep water temperature during the past three decades is similar to the global trend determined for the Northern Hemisphere (Fig. 13, Bottomley et al., 1990; IPCC, 2007; Rayner et al., 2006). Local surface water also exhibits a general temperature rise in keeping with the global rates, but with a great deal more variance (Fig. 13). The increase in deep-water temperature is keeping pace and in some cases exceeding that of the surface water.

At the decadal scale, the PDO appears to provide a significant component of variability for the NE Pacific Ocean SST: for example, based on Mantua and Hare (2002, their Fig. 1) the SST off the BC coast would have been on average anomalously cool by 0.4 ± 0.1 °C (95% CI) between 1944 and 1977 and anomalously warm by 0.3 ± 0.2 °C between 1977 and 2000. Sea surface temperature at the Nanoose Bay station correlates weakly with the PDO (Cummins and Masson, pers. comm.), its affect likely exceeded by other contributions to variability, including local factors (e.g., river inflow, solar radiation) and external effects (e.g., ENSO). Secondary contributions to decadal variability may also derive from the 18.6-year lunar nodal cycle (LNC), which leads the BC coastal SST by two years, and from the Pacific-North American (PNA) teleconnection (McKinnell and Crawford, 2007), mainly affecting January temperature and strongly anti-correlated with PDO (Yasuda, 2009). These sources of variation, which can be extracted as statistical properties of the complete temperature database, tend to be masked by short-term variability (Table 1). A comparison between an early decade (1970–1979) and the most recent decade (2003–2012) of the record shows that the increase in average *surface water* temperature at Entrance Island (+1.0 ± 0.2 °C (95% CI)) is minor compared to the annual range (~18 °C) (Fig. 14a), with a few more days/year exceeding 18 °C during the recent decade. In contrast, the increase in *deep-water* temperature (0.61 ± 0.05 (95% CI)) at the Nanoose Bay station (Fig. 14b), which is of similar magnitude to that in the surface water, is more significant when compared to the annual range in deep-water temperature (~2 °C) at that site. In fact, because the deep-water temperature has such a small annual range, the secular increase has completely shifted the frequency distribution from a peak of 8.6–9.1 °C in the 1970s to 9.1–9.9 °C in the 2000s.

Interannual variability in temperature (Fig. 11a,b) is magnified by ENSO in the intermediate and deep layers (Masson and Cummins, 2007). Episodic cold-water intrusions in winter, distinct from ENSO events, occurred in 1978–1979 and 1985–1986, but these were likely forced by local storms (i.e., events) rather than by basin-scale weather patterns.

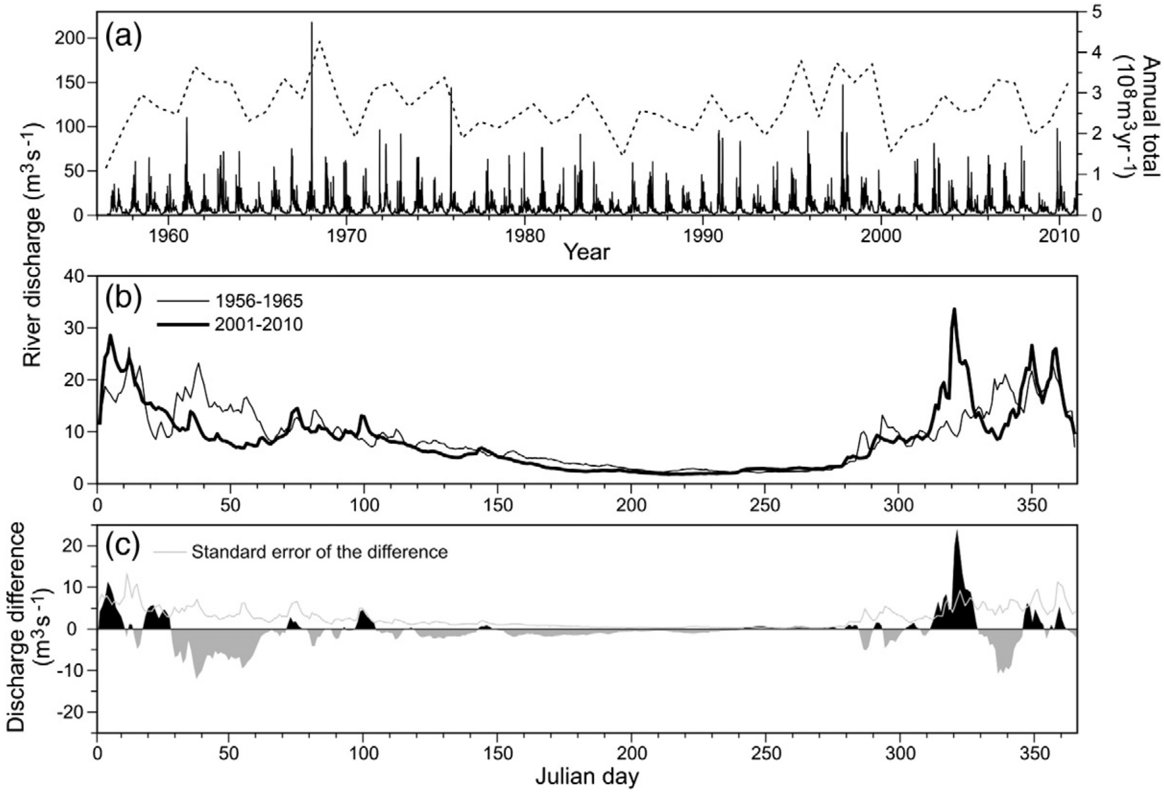

Fig. 7. Quinsam River a) river discharge and (dashed line) annual average discharge and b) the mean hydrograph (volume discharge, $m^3\ s^{-1}$) for 1956–1965 and 2001–2010; and c) the difference between the two hydrographs (latest minus earliest, $m^3\ d^{-1}$). The standard error (SE) for the difference is also plotted as a dotted line.

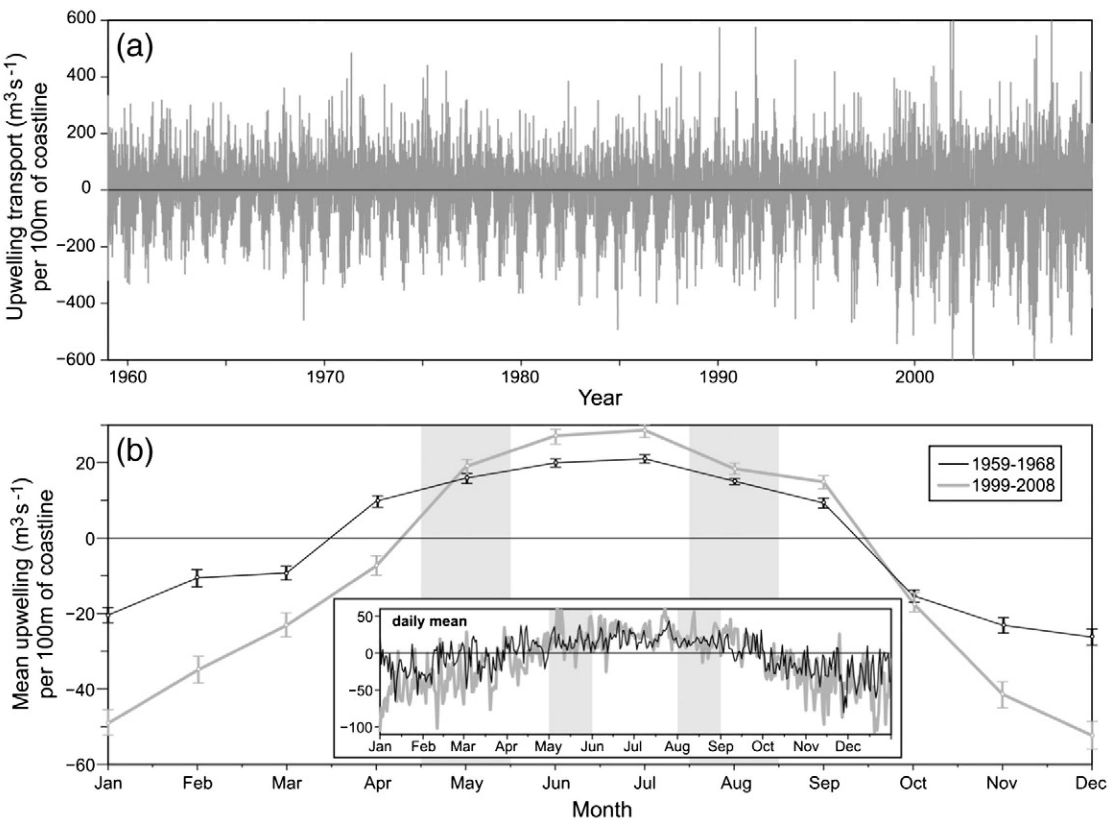

Fig. 8. Upwelling: a) the monthly average for coastal upwelling transport estimated for La Perouse station, 1959–2008; and b) monthly upwelling climatology over 1959–68 and 1999–2008, with bars indicating the standard errors for the averaged means. The grey bars indicate times of deep-water renewal in the Strait of Georgia. The inset presents the same comparison for the daily records (based on Foreman et al. (2011)). Linear regression applied independently to the upwelling and downwelling records in panel a shows increases in both over the period of record (for 100 m of coastline the annual increases for upwelling were $0.40 \pm 0.04\ m^3\ s^{-1}$ and for downwelling 0.56 ± 0.04 (95% CI)).

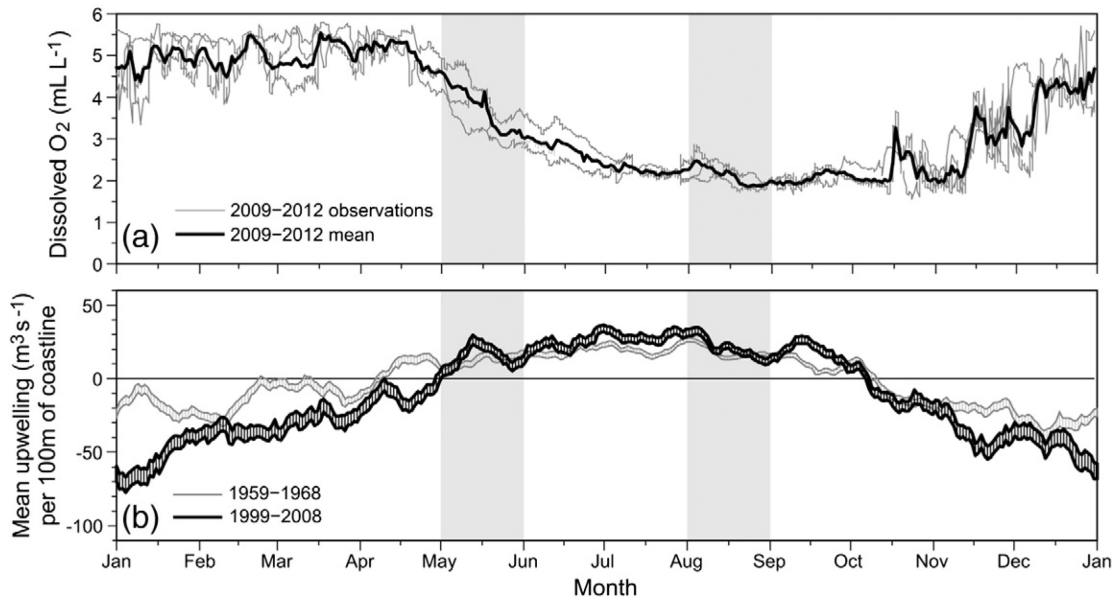

Fig. 9. The record of a) dissolved oxygen (100 m) for the Neptune Folger passage station between 2009 and 2012 and b) historical upwelling transport as represented by a moving average of the 15 days preceding the date of dissolved oxygen measurement. Grey bars show periods of deep-water renewal for the Strait of Georgia, and the width of the upwelling curves in b represent ±the standard error.

Other factors that affect temperature at seasonal or shorter time intervals include variability of estuarine circulation and Fraser plume distribution (Masson, 2002; Masson and Cummins, 2004; Pawlowicz, 2001; Pawlowicz et al., 2007), replacements of water masses through northern passages, and turbulent vertical mixing induced by wind- or flow-shear. Taken together, the variability in temperature fields is dominated by seasonal changes, with the greatest range occurring at the surface due to radiative forcing (7–20 °C), and smaller ranges at depth (±1 °C at mid water; ±0.5 °C in deep water) due to water replacements and mixing (e.g., LeBlond et al., 1991; Masson, 2002; Pawlowicz et al., 2007) (see summary in Table 1). To these seasonal variations may be added temperature variations of ~0.5–1 °C by ENSO and ±0.5 °C by PDO conditions, set against a long-term warming of ~0.6–1.0 °C since about 1980. This latter temperature increase is likely the regional manifestation in the SofG of a global ocean whose surface is generally warming at similar rates (Fig. 13).

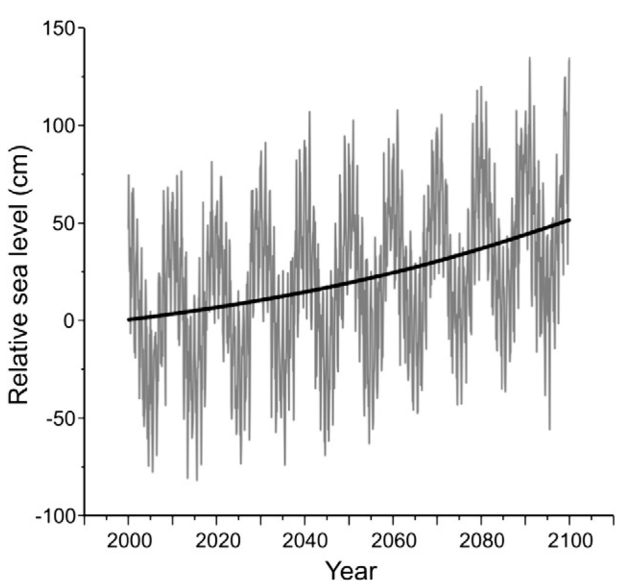

Fig. 10. A prediction of the relative sea-level rise for the coast of British Columbia (modified from Thomson et al. (2008)), showing the long-term trend proposed by IPPC (2007) and Mazzotti et al. (2008) together with an annual cycle and potential effects of ENSO. Tides and geodynamic effects are not considered in this simulation.

5.2. Salinity

Salinity in high-latitude oceans controls stratification, which is among the leading factors controlling biological processes and the ocean's contribution to climate and climate change (Carmack, 2007).

Variation in salinity in the SofG is almost entirely controlled by mixing between freshwater sources (Fraser River (~72%), other rivers (~18%), net precipitation (P-E ~ 10%), and ocean water originating from the outer coast (salinity ~ 33)) (Johannessen et al., 2003). The Fraser River annually supplies 85 ± 12 (1SD) km^3 of fresh water to the Strait, which is equivalent to a yield of 12.2 ± 1.7 (1SD) m of fresh water (assuming a surface sea area of 7000 km^2). Variations in the Fraser River discharge dominate the surface stratification of the Strait. The addition of these large quantities of fresh water to the surface of the Strait affects sea level locally (<10 cm) and forces estuarine circulation through barotropic flow out of the Strait (Godin et al., 1981; Thomson, 1994; Waldichuk, 1957).

Salinity varies strongly with water depth, because low density, buoyant fresh water enters at the surface and tends to remain there (Fig. 12). A smaller variation in salinity (~±0.2; Table 1) derives from variability in the salinity of the replacement water entering through Haro Strait (Masson, 2006). Fresh water added to the surface is distributed downward through vertical mixing, which is forced by winds, while salt is distributed upward into the surface water by estuarine entrainment. These processes produce large spatial and temporal variation in surface and mid-column water, making it difficult to detect variations in salinity due to other processes (e.g., PDO, ENSO, long-term change). In Fig. 12, the three domains in the water column identified by seasonal temperature distributions can also be seen in salinity.

Surface layer salinity at Entrance Island, near Nanaimo, responds to seasonal variation in the Fraser River inflow (Cummins, pers. comm.). The relationship between salinity and Fraser River inflow may not apply to the entire SofG (see for example comments by Peter Chandler in, Irvine and Crawford, 2012), but the sections presented by Masson (2006) suggest that much of the central and northern Strait surface waters are under significant seasonal influence of water carrying the Fraser's freshwater signal (see in particular Masson's (2006) SW_1

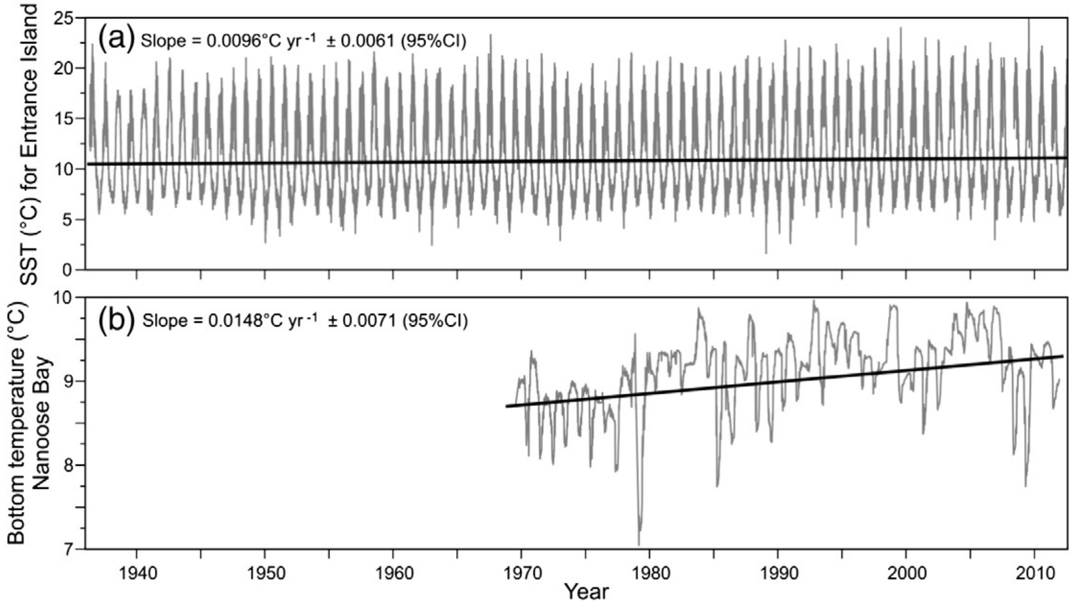

Fig. 11. The a) Sea-surface temperature at Entrance Island (off Nanaimo), 1933–2012; and b) bottom-water temperature (SST) at nearby Nanoose Bay 1970–2012. The linear regressions imply temperature increases over the periods of record of 0.40 ± 0.13 (95% CI) for Entrance Island and 0.62 ± 0.15 for Nanoose Bay.

watermass distributions). The northern region is relatively more influenced by the small-river inflow in winter (e.g., Fig. 7). Based on the Entrance Island correlation, it may be inferred that the advance observed in the Fraser River freshet (Fig. 3) is leading to earlier surface stratification of the southern SofG. It is clear, however, that salinity varies on many scales due to plume dynamics, tides and winds (e.g., see Fig. 4 in Halverson and Pawlowicz (2008) for high-resolution salinity time series showing salinity dynamics).

Salinity changes due to an advance in the Fraser River freshet may be contributing to an important systematic change to the biological functioning of the Strait. The onset of the spring bloom depends, among other things, on surface stratification (St. John et al., 1993; Yin et al., 1997). Surface temperature is also important (Hobson and McQuoid, 1997; Miller, 2004) as is light climate, which is affected by the turbidity of the inflowing water (Johannessen et al., 2006), but both of these are correlates of salinity (Johannessen et al., 2003). A hind-cast analysis of spring blooms in the SofG found that over the period of 1968–2010 blooms had been occurring earlier in the early 1990s (Allen and Wolfe, 2013), although these authors assigned the cause to weaker winds and warmer surface temperature in the SofG during this period rather than any secular trend in stratification.

5.3. Macronutrients (phosphate, nitrate/nitrite, silicic acid)

The SofG derives the vast majority of its nutrient supply from the North Pacific Ocean through basin water replacements, as discussed above for temperature and salinity (e.g., see discussions of nitrate in Mackas and Harrison, 1997; Sutton et al., 2013). Trends in macronutrients (phosphate, nitrate/nitrite, silicic acid) in the North Pacific Ocean off British Columbia (BC) were generally weak between 1987 and 2010 (Whitney, 2011). Likewise, there appears to have been little change in the resupply of these nutrients to the open-ocean's mixed layer over that time period. The only noteworthy trends that have been identified for the past few decades were a winter increase of nitrate of ~0.15 μM per year (Whitney, 2011, $p < 0.05$, eastern subarctic Pacific Ocean) and a phosphate increase of 0.15 ± 0.09 μM over a 30-

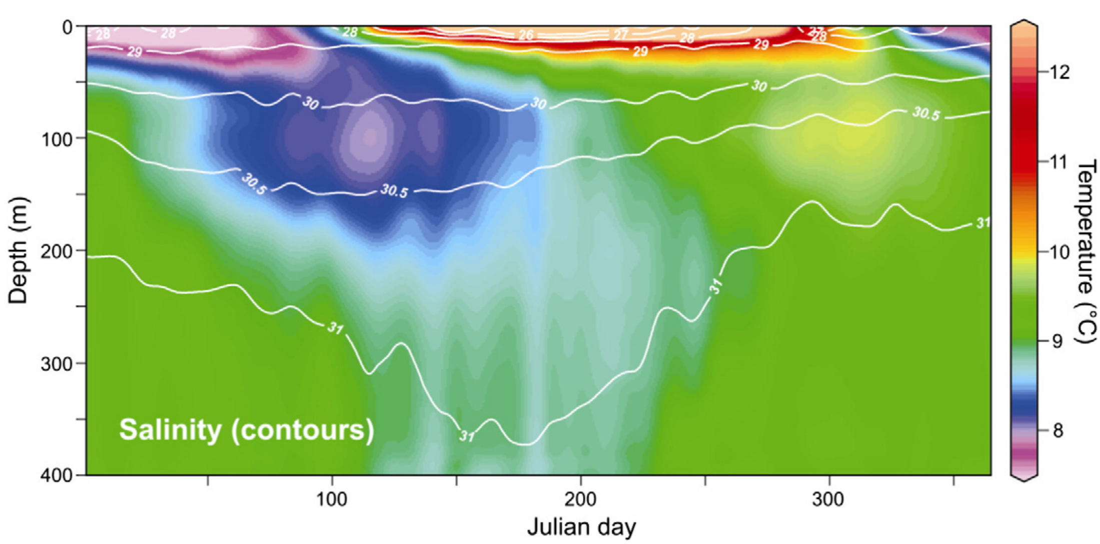

Fig. 12. The climatology of temperature (colours) and salinity (white lines) for Nanoose Bay computed from semi-monthly observations, 1970–2005. Modified from Masson and Cummins (2007).

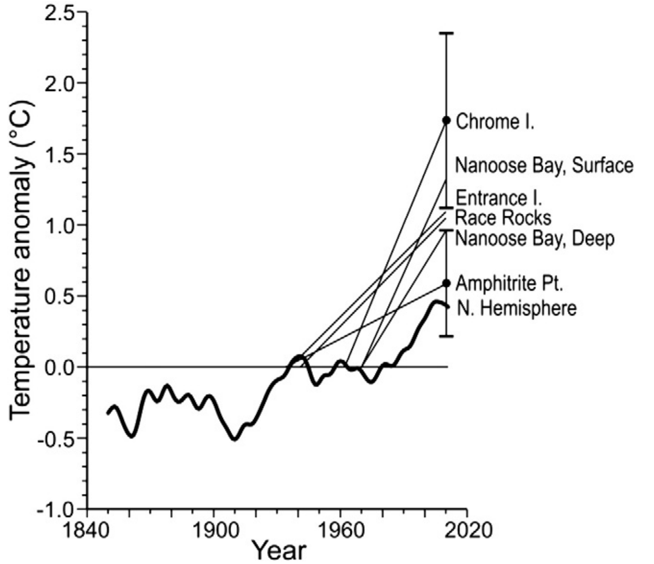

Fig. 13. Seawater temperature at the sea surface from lighthouses inside and outside the Strait of Georgia, together with Northern Hemisphere SST anomalies 1850–2011 (UK Meteorological Office, HadSST2 time series based on Rayner et al. (2006), and deep-water temperature at Nanoose Bay (Masson and Cummins, 2007)). Error estimates (bars represent ± 95% CI) are given for Chrome Island and for Amphitrite Point, the latter of which is representative of all the other stations.

year period of record (Ono et al., 2001, western subarctic Pacific Ocean). No significant trend for phosphate and silicic acid was observed by Whitney (2011). Within the SofG, an interannual variation in phosphate of 0.5 μM was observed over a three-year period (Fig. 15a, Riche, 2011) suggesting that the year-to-year variability in the Strait far exceeds any general trend observed in the Pacific Ocean water masses that supply the Strait from without. This variation is likely delivered to the basin by replacement water that derives from upwelling along the coast, which supplies watermasses with wide range in nutrient content (e.g., see Mackas et al., 1987). While trends in open ocean nutrients may contribute a small component of variance, it is the mechanics of upwelling, together with large vertical gradients for macronutrients in shelf water, that dominate variability within the Strait.

Nutrient time series in the SofG are too short to permit the evaluation of trends. However, seasonal and interannual variability is clear in a 2002–2005 record obtained near Nanoose Bay (Fig. 15, Pawlowicz et al., 2007). The most dramatic variation for all three nutrients (Table 1) occurs in surface water and can be assigned to annual drawdown of nutrients due to primary production. For the three years of measurement, spring drawdown commences in March, resulting in undetectable concentrations for nitrate and possibly phosphate by early April. The drawdown is, however, interrupted in at least two out of the three years by a sharp increase, probably the consequence of mixing events (strong winds) or, in the case of silicic acid, peak riverine load during the Fraser River freshet. The mid- and deep-water data show far less variation. At a depth of 300 m there is also evidence of seasonal decline in nutrient concentration delayed by perhaps one or two months from the surface drawdown. At that depth this decrease cannot be a signal of in-situ productivity; more likely, it is due to a change in water mass. Regeneration of products of primary production that have settled into the deeper water through vertical flux likely also imparts seasonal variation. For example phosphate increases at depth in all three years in the period following the surface bloom (Fig. 15). However, this phosphate signal might also be due to deep-water renewal.

Upwelled water contains high concentrations of nutrients and dissolved CO_2, and lower O_2 and pH (e.g., Feely et al., 2008; Ianson et al., 2009). In a water mass analysis, Mackas et al. (1987) show that water in the California Undercurrent, plausibly a strong contributor to upwelling, has modal concentrations of phosphate, nitrate and silicic acid of 2.65, 33.4 and 52 μM, respectively, and O_2 concentrations of 2.1 mL L^{-1}. Similarly, dissolved O_2 recorded between 2009 and 2012 in near-bottom (100 m) water just north of the entrance to Juan de Fuca Strait (Fig. 9a) varied from ~5 mL L^{-1} in winter to as low as 2 mL L^{-1} in summer. These O_2 concentrations reflect the cadence of upwelling and downwelling at that site (Fig. 9b).

5.4. Vertical particle flux

Rivers provide the main source of particles to the SofG (Johannessen et al., 2005). Most of this material is inorganic, consisting of ground rock. Organic particles in the SofG come approximately equally from terrigenous (land plant) and marine (phytoplankton) sources. While we lack long enough time series to comment on trends in organic flux or interactions with decadal-scale cycles, the degree of seasonal and interannual variability is clear. Sediment traps moored in the southern SofG, south of Texada Island (SOGS in Fig. 1) show that the organic flux closely follows the pattern of Fraser River discharge, with the highest flux in summer (Fig. 16a, and see Johannessen et al., 2005). In the northern Strait (SOGN), however, the Fraser River has less influence on particle flux; sinking particles in the northern basin instead reflect the discharge of local rivers and the timing of phytoplankton blooms (Fig. 16b). This separation between the northern and southern basins in the sources and timing of sinking particles leads to differences in the composition

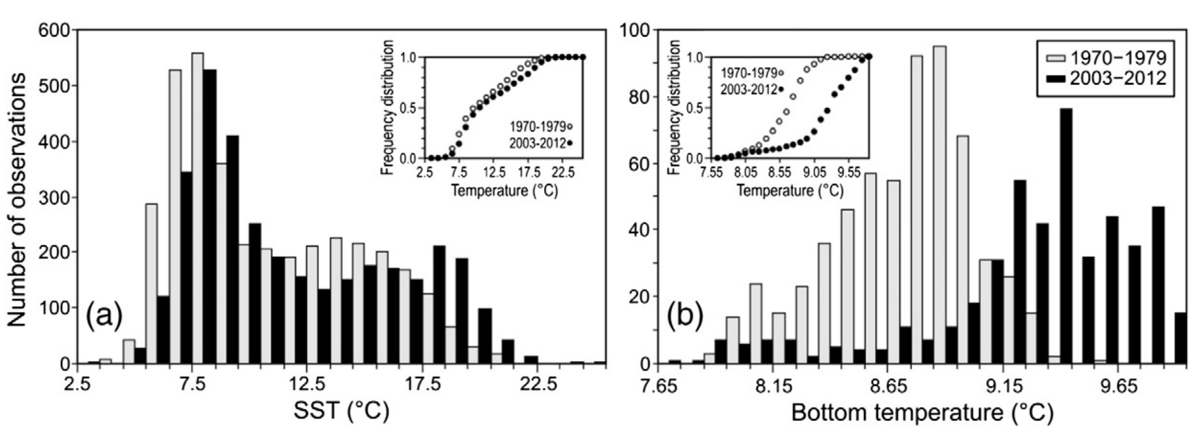

Fig. 14. Seawater temperature frequency distribution for a) surface water at Entrance Island (1970–79 compared to 2003–2012) and b) bottom water at the Nanoose Bay station (1969–1978 compared to 2002–2011). The frequency of occurrence (# of days) of any particular temperature has been calculated by including all data points falling in a T range of ±0.25 °C (panel a) or ±0.05 °C (panel b). Based on the Kolmogorov–Smirnov test, the distributions for the two time intervals are significantly different for SST ($p < 0.001$) and bottom temperature ($p \ll 0.001$) although it is clear that the bottom temperatures show the most obvious separation in T distributions. Based on t-tests assuming unequal variances, the average T is significantly higher in the later decade for SST (rising from 10.9 ± 0.13 °C (95% CI) to 11.9 ± 0.15 °C) and bottom temperature (rising from 8.68 ± 0.03 °C to 9.29 ± 0.04 °C).

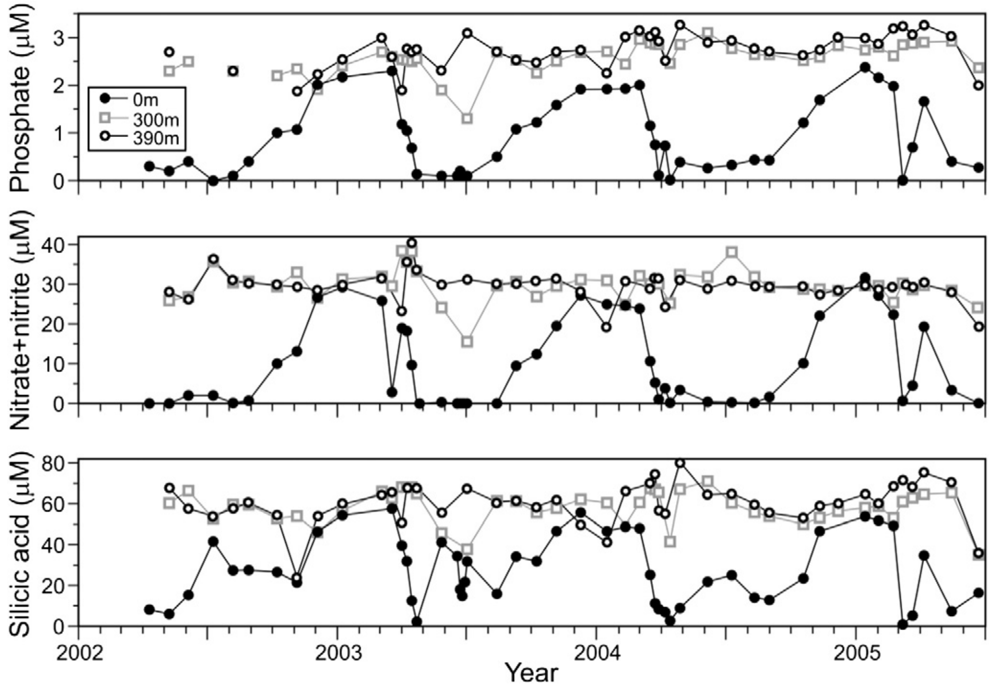

Fig. 15. Dissolved nutrients at three depths (0 m, 300 m and 390 m) at site S4-1 near Nanaimo (Fig. 1), 2002–2005. a) Phosphorus, b) nitrate and c) silicate.
Data from Pawlowicz et al. (2007).

of sinking organic matter. More of the organic matter in the northern Strait than in the south comes from phytoplankton (Sutton et al., 2013). In addition, since the peak flux of organic matter in the north is separated from the peak inorganic flux, the particles that sink in the northern Strait in the spring and summer contain a much higher concentration of organic matter, and may provide a higher quality of food in the water column. The high flux of organic matter in the mid-water column is much reduced before it reaches the bottom. Estimates based on sediment trap collections and on models of water column remineralization imply that >95% of the organic matter from primary production is remineralized before it reaches the bottom (Johannessen et al., in press; Sutton et al., 2013). However, remineralization of the small proportion of organics that does reach the deep water has the capacity to consume nearly all the oxygen that is brought into the Strait by deep-water renewal.

5.5. Dissolved O_2 and hypoxia

The concentration of dissolved O_2 (DO) in the ocean is a master variable that controls the distribution of biological species depending on their tolerance for periods of low oxygen and their ability to avoid or leave regions of low DO (e.g., Vaquer-Sunyer and Duarte, 2008). DO has recently emerged as a leading concern following evidence of widespread declines in the ocean (Falkowski et al., 2011) and expanding

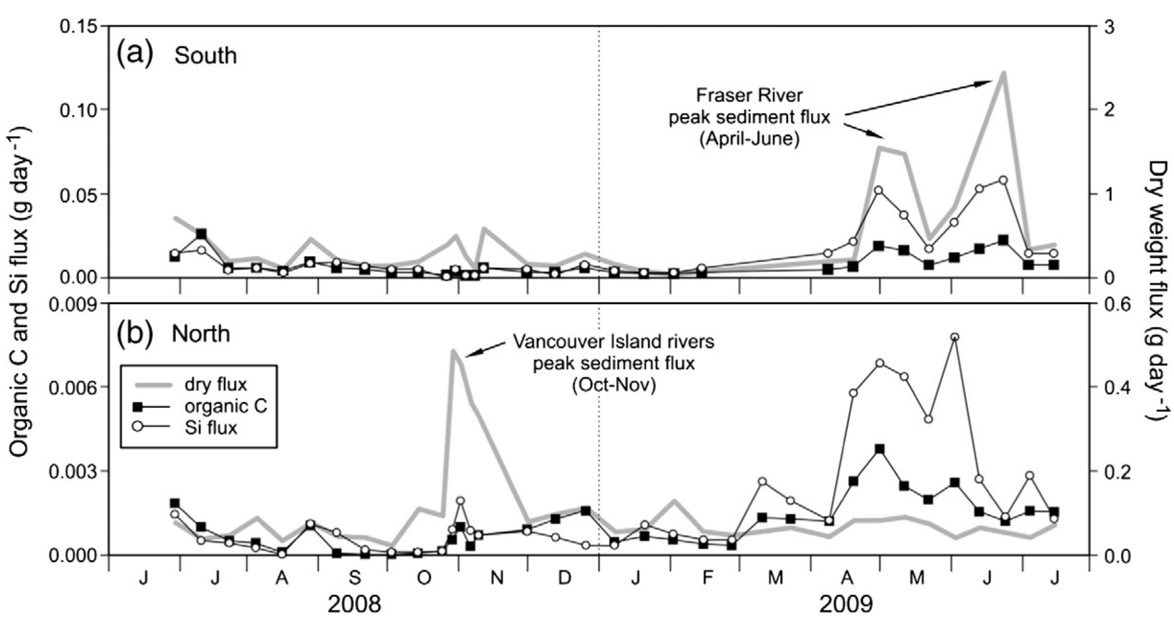

Fig. 16. Total dry weight flux (right-hand y-axis) and fluxes of organic carbon and biogenic silica (left hand y-axis) captured in sediment traps in (a) the southern (SOGS) and (b) the northern (SOGN) Strait of Georgia, June 2008–July 2009. Station locations are shown in Fig. 1.
Modified from Johannessen et al. (in press).

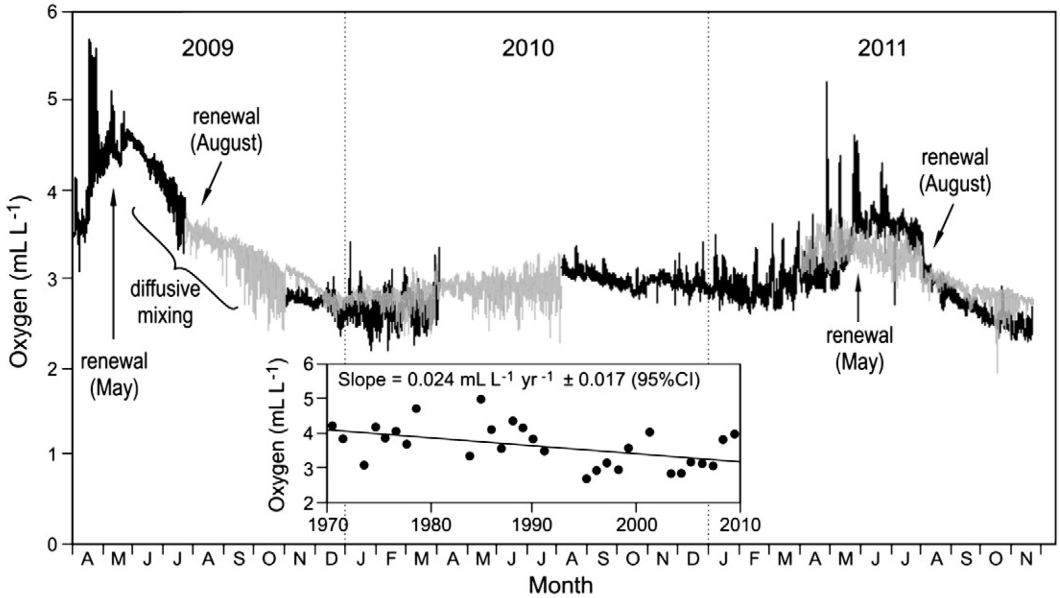

Fig. 17. Concentration of oxygen at 300 m over 2008–2011 in the southern (black line) and northern (grey line) Strait, measured at 15-minute intervals by moored sensors. Inset: Concentration of oxygen in deep water (>200 m) in May–June over 1971–2009, where each point represents the average of all dissolved oxygen measurements made in the Strait of Georgia during that season in a particular year.
Figures modified from Johannessen et al. (in press).

regions of coastal or estuarine hypoxia due to eutrophication and other factors (e.g., Gilbert et al., 2005; Turner et al., 2008). The shelf waters off the coast of BC, which supply bottom water to the SofG, have also been shown to be vulnerable to hypoxia (e.g., see Bianucci and Denman, 2012; Crawford and Peña, 2013).

Dissolved O_2 is high in surface waters of the SofG and declines with depth, partly due to low dissolved O_2 in water entering the Strait at depth, and partly due to remineralization of organic matter exported from the surface waters in the vertical flux. Recent measurements collected at a central location in the deep basin during 2002–2005 (Pawlowicz et al., 2007) show well-oxygenated water at 0–50 m (4–10 mL L^{-1})

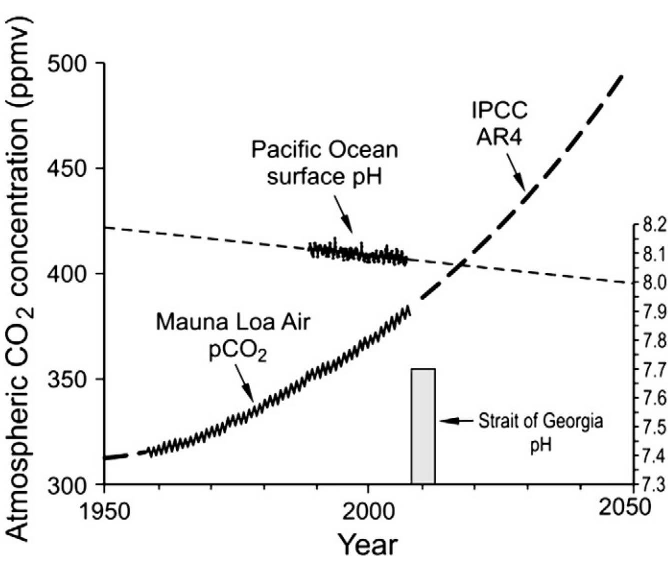

Fig. 18. The increase of atmospheric CO_2 due to the use of fossil fuels has already led to a general decline of surface ocean pH of 0.1. Rapid exchange of Strait of Georgia waters with the Pacific Ocean suggests that it is likely subject to a similar decline from pre-historic values. Projections suggest that a further decline of 0.1 pH units will occur by the end of the 21st Century. This effect on pH does not include other additive effects from, for example, enhanced metabolism of organic carbon in bottom water due to human effects on the system.
Modified from Doney et al (2009).

with episodes of low oxygen at 50 m (e.g. ~3 mL L^{-1}) in fall 2002, and oxygen-poor water below 50 m (2–5 mL L^{-1}) with hypoxic conditions at 370 m (2–4 mL L^{-1}).

Seasonally, the concentration of DO in surface water is highest in the late spring, due partly to low surface temperatures in the SofG remaining at end of winter and partly to the ramp-up of in situ production by phytoplankton. The deep water also has a marked seasonality in DO (Fig. 17), but this is unrelated to the processes occurring in the local surface waters. In late spring and late summer each year, deep-water renewal events replace the bottom water (Masson, 2002). During the late spring renewal, which generally takes place in May although sometimes earlier, the inflowing deep-water has a much higher DO than does the ambient water. The DO peak introduced by deep-water renewal is rapidly reduced by diffusive mixing with the surrounding water and is also reduced more gradually by remineralization throughout the year (Johannessen et al., in press) (Fig. 17). The inflowing water has a high concentration of oxygen, because the hypoxic source water (upwelled onto the shelf at the mouth of Juan de Fuca Strait) is mixed with surface water during the energetic tidal mixing in Haro Strait. During the second deep-water renewal, in late summer, the concentration of oxygen in the replacement water is lower than it is in spring, because by that time the surface water in Haro Strait is warmer and has a lower concentration of oxygen to contribute to the mixture (Johannessen et al., in press) and probably also because the shelf water is more upwelled during that season, therefore containing less dissolved oxygen.

Although seasonal variability predominates in both the surface and deep water of the Strait, the concentration of oxygen has also been changing gradually over time. Over 1971–2009, the concentration of oxygen in the deep basins of the Strait declined by about 0.02 mL L^{-1} yr^{-1} (Fig. 17 inset), reducing the seasonal minimum from about 3.5 mL L^{-1} in the 1970s to about 2.5 mL L^{-1} today (Johannessen et al., in press). The main driver of this decline has been a reduction in the concentration of oxygen in the upwelled source water, rather than an increase in the local discharge of nutrients or organic carbon.

5.6. pH and ocean acidification

As a consequence of the long-term trend of increasing CO_2 in the atmosphere (IPCC, 2007), the global surface ocean has been taking up CO_2

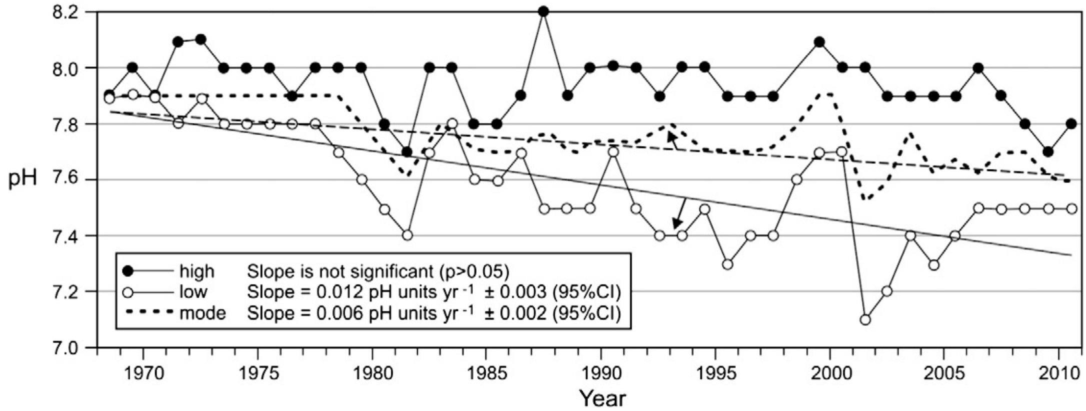

Fig. 19. A time series for pH collected by the Vancouver aquarium.
Modified from Marliave et al. (2011).

since the start of the industrial revolution. Carbonic acid, produced by the dissolution of CO_2 in water, leads to ocean acidification. The Global Ocean has now reached the point where significant changes in the carbon chemistry of surface waters can be detected (0.1 pH unit or 30% more H+, Fig. 18, Dore et al., 2009), and these changes may already be having effects on marine biota (Denman et al., 2011; Doney et al., 2009; Guinotte and Fabry, 2008).

We lack data from the SofG that would allow us to determine recent trends in pH, however the emergent evidence appears to indicate that coastal regions may be more vulnerable to the impacts of acidification due to a number of reasons including complex oceanography, the addition of poorly buffered freshwater and added stresses from nearby human activities (e.g., see Cai et al., 2011; Gruber et al., 2012). The current range of pH is wide (Fig. 18), extending from >8.2 near the surface during periods of high productivity, to less than 7.3 in near bottom waters (Johannessen, unpublished data). Clearly, the coastal ocean generally manifests a greater range in pH than the open ocean due to the many processes associated with land–ocean interactions including especially river inflow and human activities (e.g., see Duarte et al., 2013). Dissolved oxygen and pH are tightly linked because respiration both consumes oxygen and produces CO_2, which reduces pH, while photosynthesis has the opposite effects. Consequently, where oxygen concentrations are low, one expects pH also to be low. A unique pH time series for Vancouver Harbour, adjacent to the Strait of Georgia, maintained by the Vancouver Aquarium since 1968 (Fig. 19, Marliave et al., 2011) suggests that average pH might have declined by about -0.3 ± 0.1 pH units over the period of record, which corresponds to approximately a doubling of $[H^+]$. This rate of decrease would suffice to produce a significant environmental consequence within the local ecosystem (Harley et al., 2006).

In Puget Sound, recent measurements imply that acidification has already occurred, possibly at rates faster than in the open ocean, due partly to loading of anthropogenic CO_2 and partly to enhanced metabolism of organic matter originating from human activities (Feely et al., 2010). These authors calculate that aragonite, a solid form of carbonate used by pteropods and other important planktonic organisms, may already be unstable and prone to dissolution.

Both the degree and effect of acidification will depend on local factors. For the SofG, the alkalinity and $[Ca^{++}]$ of fresh water from the Fraser River will be crucial.

6. Discussion

Every time series presented above reveals a dominant variation at the seasonal scale (Table 1), although the timing, intensity and cause of seasonal variability differ among properties. Strong seasonal or shorter-term variability has the potential to cause properties to cross tipping points earlier than would be predicted from the trend in the average conditions alone. Tipping points may occur in water properties, such as DO and T, or in synchronicity, as in the timing of entry of predator and prey. Dissolved oxygen presents a case where a long-term trend may have no noticeable biological effect until suddenly a threshold is crossed. For DO there is potentially a range in tipping points depending on species, but 1.4 mL L^{-1} (60 μmol L^{-1}) is often given as a hypoxic boundary beyond which many animals show effects (e.g., Vaquer-Sunyer and Duarte, 2008). If, in the SofG, the average deep-water oxygen continues to decline, hypoxia could begin to manifest, first as intermittent episodes. Interannual variability in deep-water oxygen concentration, which appears to be large (inset to Fig. 17), suggests that such episodes would begin to occur well in advance of enduring hypoxia (and see Johannessen et al., in press). The mechanics of the seasonal replacement process, however, may prevent deep-water from becoming hypoxic. A model simulation shows that because the replacement water mixes with surface water in Haro Strait, the concentration of oxygen in the deep SofG would probably level off just above 2 mL L^{-1}, even were the source water to become anoxic (Johannessen et al., in press). In the event that deep-water does go episodically hypoxic, seasonal replacement would at least limit the duration of hypoxic conditions each year.

The seasonal range in T is greater than the average increase over several decades (Table 1), but it may be the maximum T that matters to marine biota. Accordingly, even a relatively small long-term increase in the average T may lead to seasonal maxima in T that cross biological tipping points. It is unclear what effect temperature rise will have on the ecosystem, but it seems certain that increased average temperature will, among other factors, set the stage for invasive species (Chapman, 2012; DiBacco et al., 2012; Occhipinti-Ambrogi, 2007). In addition, the increase in summer temperatures of the Fraser River could spell the demise of temperature-sensitive species like sockeye salmon (Rand et al., 2006), which then have effects on their predator or prey species within the SofG. And in the deep water, animals that are adapted for low temperatures will become less tolerant to hypoxia or low pH as the water temperature increases (Pörtner, 2001).

Seasonal variation in surface-water salinity in the SofG is due mostly to variation in Fraser River inflow, and therefore much of the spatial variability in the Strait is a product of a seasonal inflow distributed unevenly by winds and plume dynamics. Biota in the SofG is likely adapted to a wide range in salinity, and therefore small shifts in mean salinity conditions are not likely to pose any direct threat. In contrast, the *timing and depth* of strong stratification in spring could be important to annual primary and secondary production for the entire Strait. Seen in that light, the shift in hydrology evident in Fig. 3c implies that stratification of the Strait has advanced by several weeks over the period of record, and this advance is projected to increase even more in the future (Morrison et al., 2002). Toward the end of the 21st Century, late summer flows for glacier-fed rivers are projected to decline due to a general wastage of the world's continental ice masses (e.g., see for example, Bradley, 2011; Sharp et al., 2011). While these glaciers would contribute a relatively minor component of sea-level rise (Huss and Farinotti, 2012), they represent an exceptionally important late-season buffering for stream flow in mountainous regions, which clearly applies to the Fraser and most other BC rivers. Adding to this stress would be the generally drier summers projected in the coming century for western Canada (IPCC, 2007). Human intervention in the future presents a 'wild card' in the form of water released from reservoirs during dry/warm summers to preserve salmon migrations or supply irrigation, but all the indicators suggest that significant, sustained change in the lower trophic levels of the Strait is a possible consequence of a changing hydrology in the Fraser and other rivers.

A seasonal or sub-seasonal timescale dominates variations in macronutrients (NO_3, PO_4, $Si(OH)_4$), dissolved O_2 (hypoxia) and likely pH. A temporal record of change in the Strait's biogeochemical cycle is more thoroughly understood by viewing it as an ensemble of linked changes in the biological system components. For example, blooms in surface water remove nutrients, convert CO_2 and H^+ ions to organic matter, and release O_2. The major variation in surface water with time is the strongly coincident drawdown of PO_4, NO_3 and $Si(OH)_4$ in spring with drawdown ratios of ~P:N:Si = 1:15:28 (Fig. 15: inverse modelling of nutrient drawdown during spring primary production yields uncertainty estimates of N:P = 14.6 ± 0.8 and Si:P = 28.1 ± 3.8 (see Chapter 5 in Riche, 2011)). Episodic renewals, likely driven by wind-mixing events (e.g., the coincident rise in P, N and Si in April, 2005), cause short-lived increases in nutrient concentrations. Silicate has an extra component of variability due to $Si(OH)_4$ supply by the Fraser River (40–60 μmol L^{-1}) and to changes in plankton composition (diatoms vs. flagellates).

Vertical flux transports a small component of the particulate organic matter out of the surface layer, and the influence of blooms and river discharge is strongly apparent in the variation in organic flux at 50 m (Fig. 16). pH (acidification) and dissolved O_2 (hypoxia) in deep water depend in part on regeneration of the subsequent rain of biogenic particles. However, although the burst of surface productivity may occur over only a few weeks, remineralization at depth continues throughout the year, obscuring linkages between surface and deep cycles. At 300 m during and after the spring bloom, when regeneration of raining particulates should be occurring, we see a decline, not an increase, in all nutrients (Fig. 15), implying that variance at this depth is predominantly controlled by exchange with water from Juan de Fuca Strait, rather than by the SofG's internal biological cycle.

Interacting with the variation at all scales is the residence time of the water in the SofG. The residence time of the water in the Strait is short (a few days in the plume, a few weeks in surface water, and up to a year for basin water (Pawlowicz et al., 2007)). Because the water has a short memory (less than a year or two) for local effects, human activities adjacent to the basin (e.g., nutrient or organic carbon loadings) or an increase in primary production at the surface would have to be sustained or escalating to produce a long-term trend within the Strait. The rapid replacement of water in the Strait by Pacific Ocean water passing over the outer shelf implies that trends in surface layer of the north Pacific and variability in processes on the shelf (upwelling/mixing) are important pre-cursors to conditions in the Strait, as are variations in the Fraser River discharge. Since the deep-water renewal events that replace the DO in deep water are driven independently from variations at the surface, it appears to be only coincidental that the amount of DO consumed in a year is very similar to that added by deep-water renewal (Johannessen et al., in press). Consequently, even a small trend in DO has the potential eventually to push the seasonal DO minimum into hypoxia.

Tipping points can also occur in synchronicity, driven by mismatched changes in timing. If the timing of the zooplankton bloom changes independently from that of the phytoplankton, there is a risk of a mismatch in timing between grazer and food, which could be disastrous for zooplankton that cannot adapt. The dramatic change in the timing of the zooplankton bloom (~60 days earlier in the early 2000s than in the 1970s (Rana El_Sabaawi, personal communication)), which has not been accompanied by a similarly large shift in phytoplankton timing, may have caused or may yet cause the crossing of a tipping point in synchronicity. Similarly, juvenile salmon may emerge from their natal streams too late to take advantage of the increasingly early zooplankton bloom, thus contributing to declining – or episodically low – returns. The effects of such a timing mismatch with zooplankton are already apparent for migratory seabirds.

Plankton reflect oceanographic conditions (e.g., T, S, nutrients), exhibiting strong seasonal and interannual variation in biomass and composition in the Strait of Georgia (e.g., see El-Sabaawi et al., 2012, 2013; Hobson and McQuoid, 1997; Li et al., 2013; Mackas et al., 2013). The complexity of connections between physical variables, phytoplankton, zooplankton and higher trophic levels renders it difficult to assign cause of biological change/variability in the higher trophic levels; however, temperature (e.g., Hobson and McQuoid, 1997) and phytoplankton composition/abundance (e.g., Parsons and Whitney, 2012) could both have opportunity to play a role. Relatively long zooplankton time series (e.g., Mackas et al. (2013) analyse a 50-year record for the Strait) show changes during the past two decades. In particular, copepods, euphausids and most other taxa had biomass minima in 1995–1996, recovered during 1998–2002, and then exhibited minima again in 2004–2007 (Mackas et al., 2013, their Fig. 14). These authors found a positive correlation with the North Pacific Gyre Oscillation (NPGO), a climate index developed specifically to link decadal-scale physical and ecological variability in the North Pacific (Di Lorenzo et al., 2008).

Control studies suggest that shifts in the upper trophic levels propagate from lower trophic levels (El-Sabaawi et al., 2012; Li et al., 2013; Schweigert et al., 2013; Therriault et al., 2009) and, accordingly, low trophic level fluctuations have been used partly to explain fisheries regime shifts in the Strait of Georgia (Li et al., 2013; Schweigert et al., 2013; Therriault et al., 2009) because herring spawning timing and juvenile survival rate strongly depend on the timing of zooplankton blooms (El-Sabaawi et al., 2012; Schweigert et al., 2013; Therriault et al., 2009).

7. Conclusions

Timing is everything in the SofG. The cadence of the seasons maintains a delicate balance in the geochemical and biological cycles. Seasonal variability predominates both at the surface and in deep water, albeit driven by different factors in the two environments. At the surface, the onset of the Fraser River freshet and the timing of late winter windstorms determine the timing and strength of surface stratification, which, together with the lengthening days of spring, set the timing for the spring phytoplankton bloom. Zooplankton then bloom, prompted by other changes, possibly including the temperature of deep water, and graze on the phytoplankton. Juvenile fish emerge from their natal streams and prey on the zooplankton.

As the organic matter from the surface production sinks, kinetics dictates that it is almost entirely (~96%) decomposed before it reaches the deep basins of the Strait. Once there, it continues to decompose, consuming oxygen. Each year, the winter oxygen minimum is about 2.0–2.5 mL L^{-1}, poised just above the level where hypoxic effects become common. The residence time of the intermediate and deep water (a few weeks and a year, respectively) is short enough for the oxygen to be replaced just before it is all consumed by the remineralization of the rain of organic particles from above. Then, in spring (March–May, but usually May), deep-water renewal events replace the deep water, injecting enough oxygen to last for another year.

The strong seasonal signal is reduced or augmented by decadal-scale climate oscillations, such as the Pacific Decadal Oscillation (PDO) and El

Nino Southern Oscillation (ENSO), depending on their phase. The decadal variability due to the PDO strongly interacts with interannual variability due to ENSO when they are in phase. The PDO warm phase tends to bring earlier freshet, while the cold phase brings later freshet, and upwelling- or downwelling-favourable winds during ENSO/PDO events can also modulate the salinity of dense water intrusions in the SofG.

The wide range of seasonal variability masks the effects of long-term change and slows or obscures the approach to thresholds. Major trends in the SofG are: warming of seawater and river water, declining deep-water oxygen, rising sea level, a change in the timing of the Fraser River freshet, and likely declining pH. The warming of surface seawater and river water in the Georgia Basin over the past few decades, for example, has been somewhat less than the seasonal range in temperature, but it is moving the seasonal range upwards. Deep-water oxygen has declined over the last 40 years, but the seasonal renewal by water that has been reoxygenated through mixing with surface water – an unusual feature of the SofG compared with other coastal areas – has slowed the decline. Relative sea level, which has risen by more than 12 m over the last 8000 years, is expected to rise by a further 60 cm by the end of the century. Although an order of magnitude less than that of the tidal range near Vancouver (5 m daily maximal tidal range, Point Atkinson station), this increase together with more frequent/intense storms will lead to greater encroachment of shore zones by the sea. The Fraser Delta is particularly vulnerable due to the low gradient of the land, poorly consolidated sediment and use of this area by industry and residential development. We lack long-term records of pH (and carbonate system) in the Strait, but in the nearby Northeast Pacific, the decline over the last 43 years has been ~0.1 pH units, a relatively small change compared with the ~0.5 range in pH below the 100 m depth in the SofG or the similar seasonal range observed in surface water. The continued global increase in pCO_2, however, will cause environmental conditions to cross significant biological thresholds, or tipping points, probably as rare events at first, but then more frequently. There is an urgent need to quantify the ecological resilience of coastal waters, like those of the SofG, in terms of sensitivity to temporal trends and tipping points between stable states, and to determine the degree of reversibility when tipping points are crossed (Groffman et al., 2006; Swaney et al., 2012).

The significance of the relatively small changes over the long-term, together with the overwhelming seasonal variability in the same properties, has implications for effective monitoring of change in the SofG, and in other coastal seas. Variation declines with depth in the water, and seasonal variation at depth tends to lag seasonal variation at the surface. In the deep basin, properties are predominantly imported from outside the Strait, and there is only a muted opportunity for surface processes to introduce variation through, for example, vertical diffusion and particle flux. Under these circumstances, it is an easier task to sample for – and demonstrate – statistically significant temporal trends in the deep water than in water from shallower layers. Unfortunately, the corollary to this statement is that trends in basin water will provide an insecure basis to infer trends that might be occurring in some of the important processes near the surface.

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